Complex Networks/ Foundations of Information Systems

6 March 2013

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Integrity ★ Service ★ Excellence

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2013 Spring Review

NAME: Complex Networks/Foundations of Information Systems

BRIEF DESCRIPTION OF PORTFOLIO:

Complex Networks and Foundations of Information Systems uses measured information to assure, manage, predict, and design distributed networks, systems, and architectures

LIST SUB-AREAS IN PORTFOLIO:

- *Local Network Research*: Guarantee and assure information transmission
- *Network Management Research*: Network and system protocols for resilient and robust
- *Global Network Research*: Mathematically represent network performance and design robustness
- *Foundations of Information Systems Research*: Measure, predict, and verify information system properties

Complex Networks & Foundations of Information Systems

Goals:

- ***Measure*** **system performance and** ***calculate risk***
- ***Preserve critical information structure*** **and minimize latency over a heterogeneous distributed network and system**
- ***Ensure network and system robustness and resilience*** **under a diverse set of resource** ***constraints*** **and manage using dynamic models**
- **Represent global properties of a networked system in a** ***unified mathematical framework*** **for architecture and design**
- ***Assess and Predict*** **heterogeneous distributed systems performance using unified mathematical framework**

Foundations Goals	Complex Networks Goals

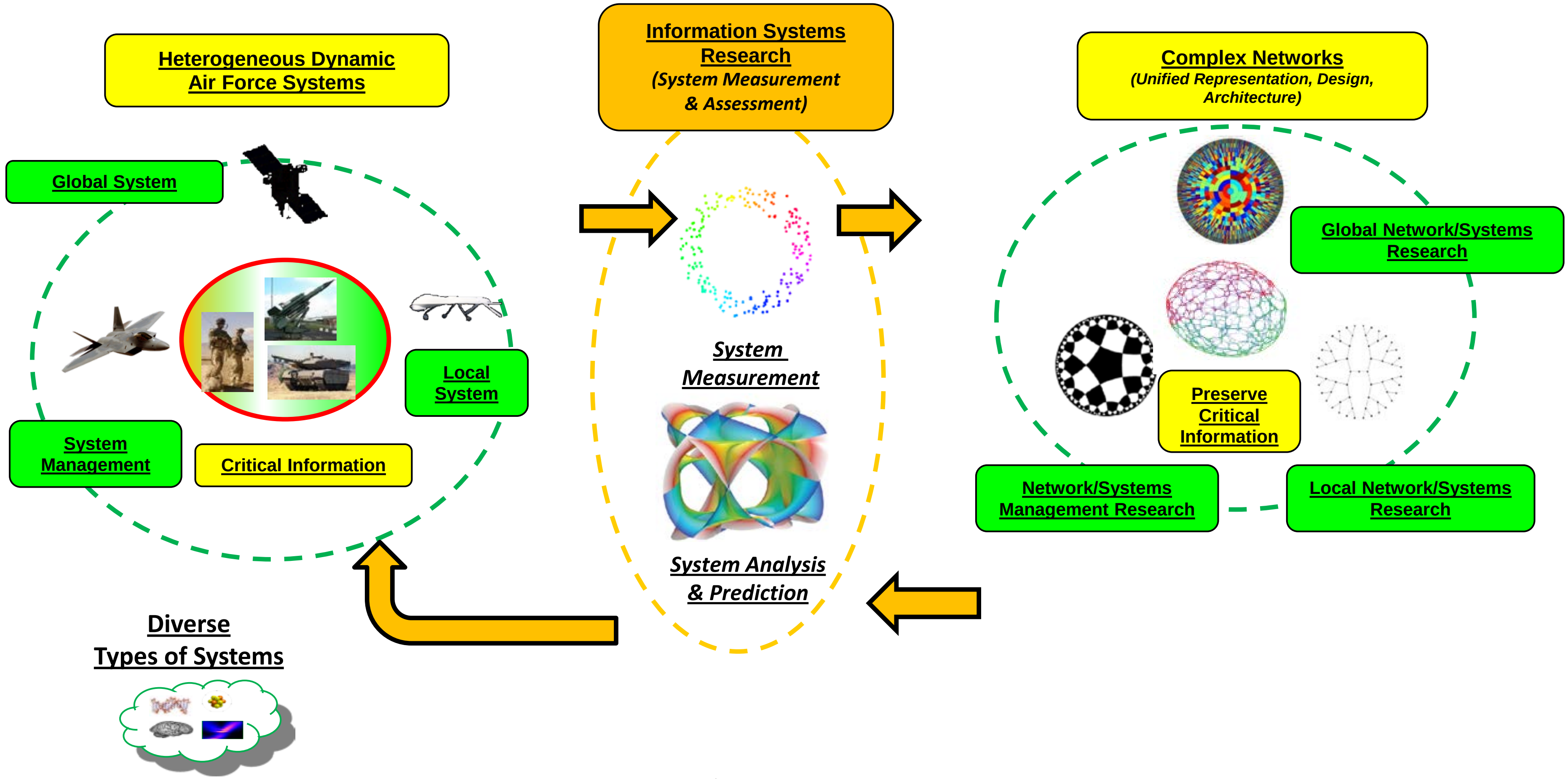
Complex Networks & Foundations of Information Systems

Payoffs:

- **Preserve critical information structure in a network rather than just delivering packets or bits**
- **Quantify likelihood of a given network management policy to support critical mission functions**
- **Predict and manage network and system failure comprehensively**
- **Assess and verify properties of a distributed heterogeneous system where there is limited access to its elements**
- **Assess dynamic Air Force system mission performance and assess risk of failure**

Complex Networks and Information Systems Roadmap

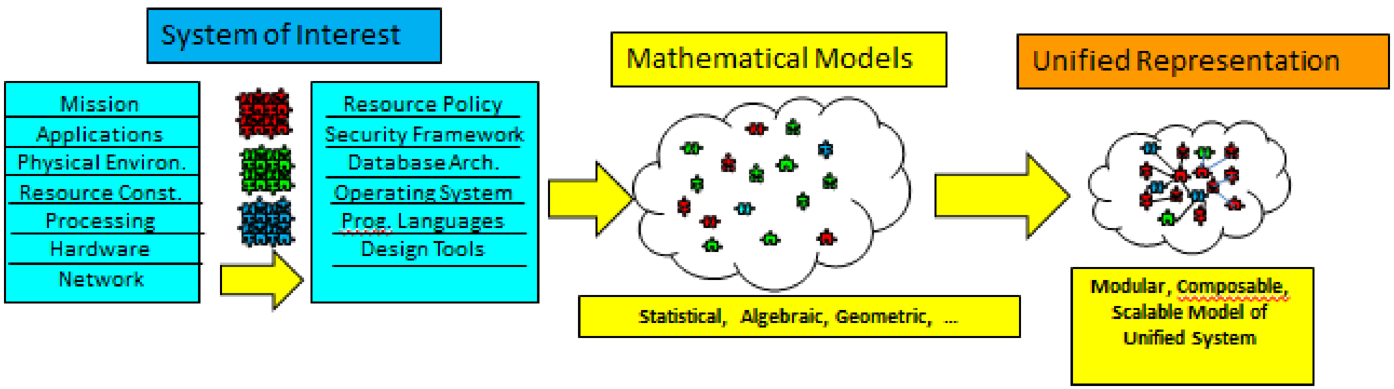
Complex Networks and Information Systems uses measured information to assure, manage, predict, and design distributed networks, systems, and architectures



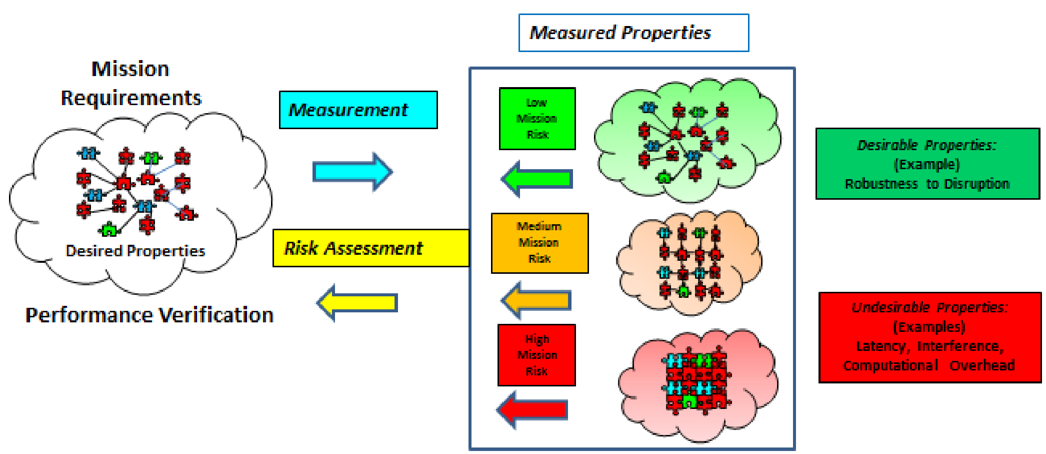
Information Systems Measurement

We wish to understand what and how to measure systems for representations that are traceable to mission performance and have quantifiable risk

What to measure?



How to measure?



System Measurement and Probabilistic Model Checking

Ed Clarke, CMU, David Musliner, SIFT

Approach: Techniques on what and how to measure on any software, network, and hardware integrated system with probabilistic model checking.

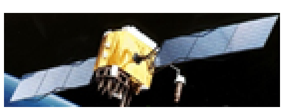
Payoff: Large system state spaces can be verified and risk calculated in a computationally efficient way.

Heterogeneous Systems

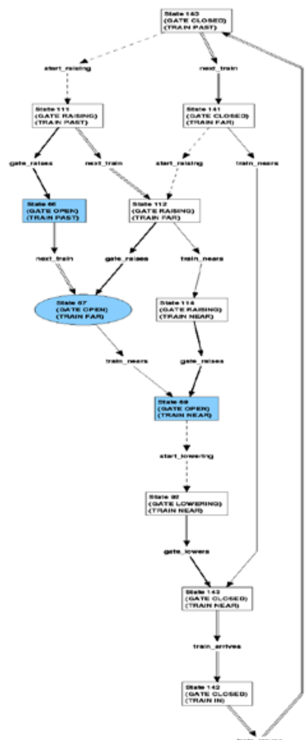
Pilot's Associate

Cyber Security

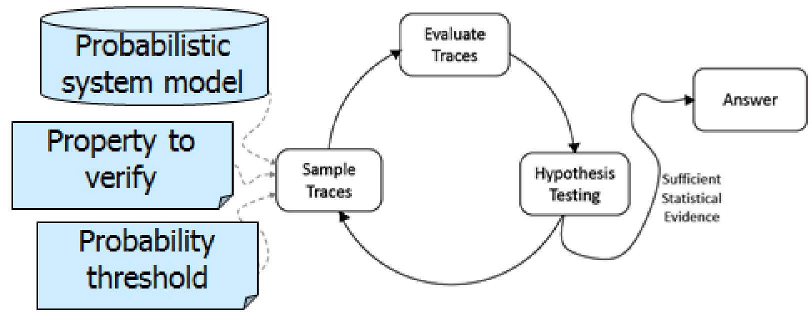
Spacecraft Autonomy



Dynamic System Model of Critical System Parameters

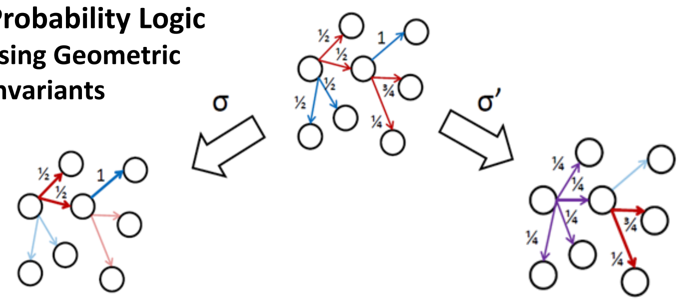


Toward Online System Analysis With Measurement



Probabilistic System Prediction and System Risk Analysis

System Probability Logic State Using Geometric Invariants



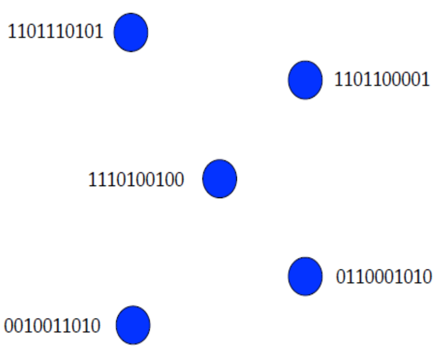
Accurate Measurement of Systems Graph Parameters

Dan Speilman, Yale

Approach: There are many different ways to represent networked systems. There needs to be a principled way of selecting the best inputs for geometric models to parameterize system performance.

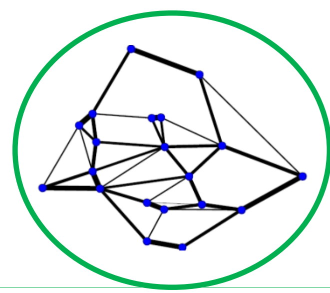
Payoff: Systems can be parameterized in such a way as to minimize computational overhead and inaccuracies in model prediction using sparse geometric graph theory.

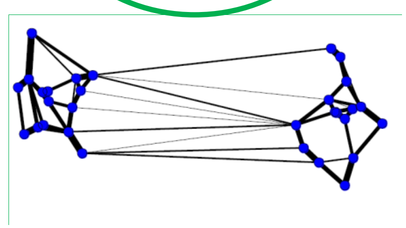
Critical Systems Information



Best Model?

Sparse Regression of Graph To Build Best Geometric Model





Best System Parameterization

$$\sum_{i=1}^{n} d_i ||\boldsymbol{x}_i - \frac{1}{d_i} \sum_{j \sim i} w_{i,j} \boldsymbol{x}_j||^2$$

$$= \sum_{i=1}^{n} ||d_i \boldsymbol{x}_i - \sum_{j \sim i} w_{i,j} \boldsymbol{x}_j||^2$$

Subject to $d_i \geq 1, \forall i$

MacArthur Genius Award Winner 2012

Statistical System Estimation and Risk Analysis

Eric Kolaczyk, Boston University

Approach: Sample large systems guided by understanding of geometric invariants and risk analysis in how measurements were constructed.
Payoff: Minimum risk can be incurred from measurements of large system while still sampling in most computationally efficient way.

Minimum Risk Outcome for Graph Sampling

The Underlying Network-Graph $G = (V, E)$	The Inferred Network-Graph $\hat{G} = \left(V, \hat{E}\right)$
Underlying Graph Characteristic $\eta(G)$	Inferred Graph Characteristic $\eta\left(\hat{G}\right)$

- Let G be a connected, undirected binary graph
- Express the relationship between $G = G_{true}$ and $\hat{G} = G_{observed}$, in terms of their $n \times n$ adjacency matices, as

$$W_{observed} = W_{true} + W_{noise}$$

  where W_{noise} captures Type I and Type II errors.

- **Our Goal:** Construct an estimator $\widehat{W}$ of W_{true} from $W_{observed}$ for which

$$||f\left(\widehat{W}\right) - f\left(W_{true}\right)|| << ||f\left(W_{observed}\right) - f\left(W_{true}\right)||$$

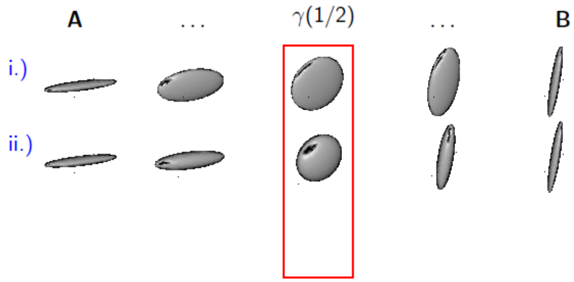
  for any *smooth* statistic $f(W)$.

Geometric Strategies for Sampling Graph

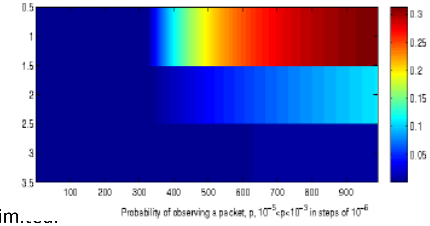
Matrix Geodesics ($\alpha \in [0, 1]$)

i.) *Euclidean geodesic:* $\gamma(\alpha) = \alpha\mathbf{A} + (\alpha - 1)\mathbf{B}$.

ii.) *Log-Euclidean geodesic:* $\gamma(\alpha) = \exp\left(\alpha\mathbf{A} + (1 - \alpha)\mathbf{B}\right)$.

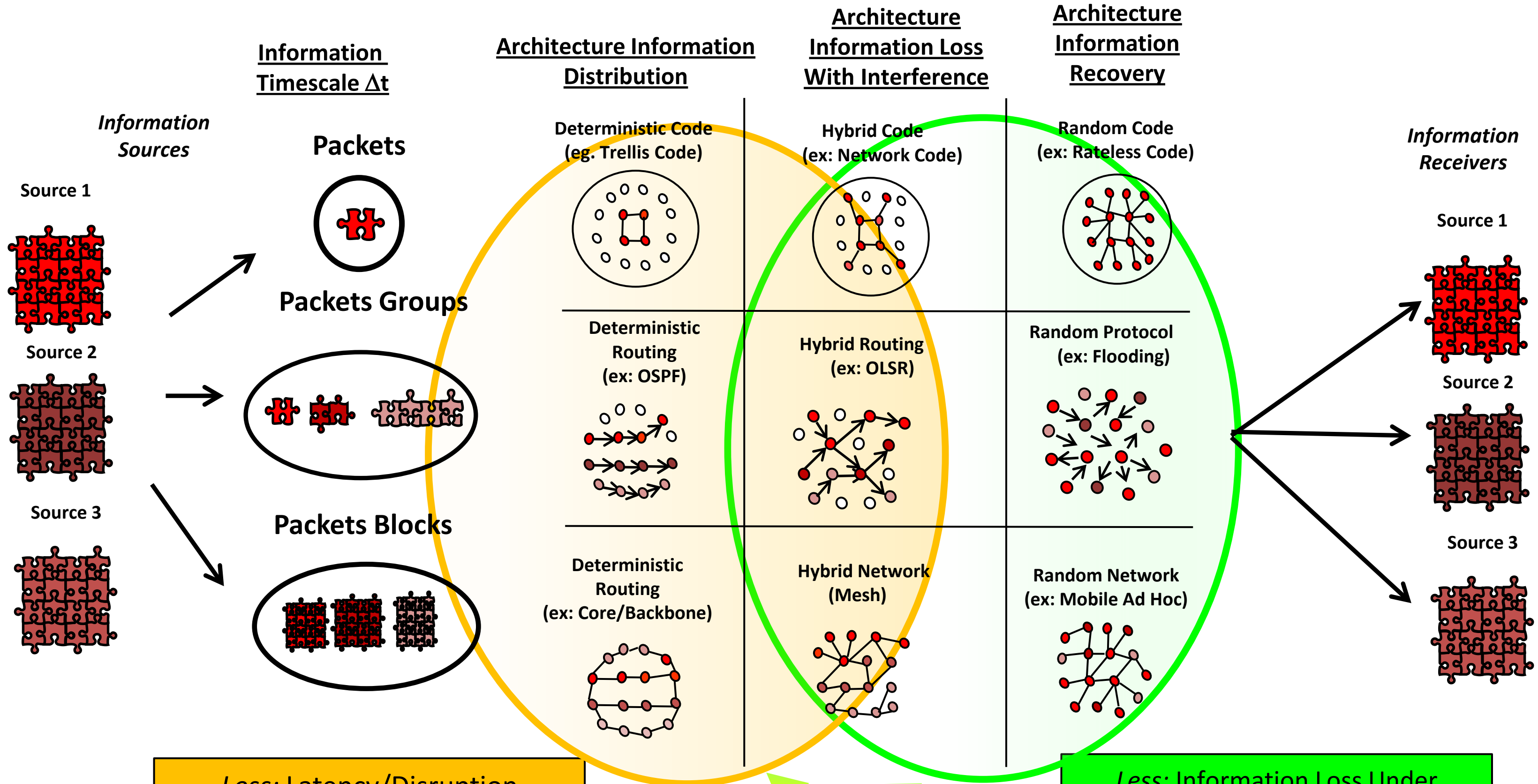


Risk Performance Peer to Peer Network Data



Complex Networks
System Representation

• **We wish to characterize network and system performance from measurement and develop coding, protocol, and architectures that adapt according to network/system state**



Less: Latency/Disruption Tolerant
More: Controllable

Algorithm State Adapts According to Conditions (Feedback)

Less: Information Loss Under Disruption
More: Latency, Resource Intensive

Network Taxonomy

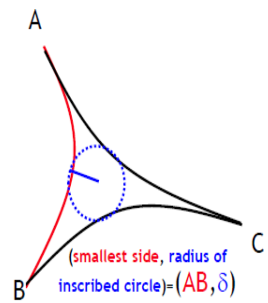
Narayan, Saniee UC Santa Cruz/Lucent

Approach: Develop a taxonomy of network properties through curvature and timescale invariants from hyperbolic geometry

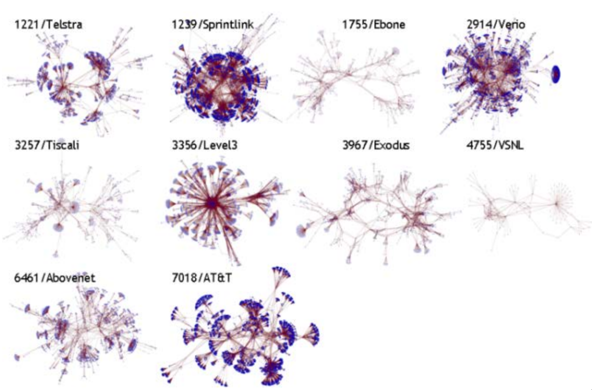
Payoff: Space of network models can be developed and design principles and analysis algorithms derived to predict network behavior

Geometric Curvature Invariant

1. 3-point "Triangle test" - Are triangles universally δ-thin?
   - Select triangles
   - For each triangle note shortest side L and computed the δ
   - Counted number of such triangles, indexed by δ and L



Taxonomy of Physical Architecture Across Networks

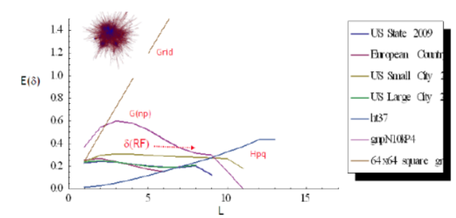


Characterization of Network Stack Across Layers (curvature connected to congestions)

Curvature vs. Timescale and Network Layer

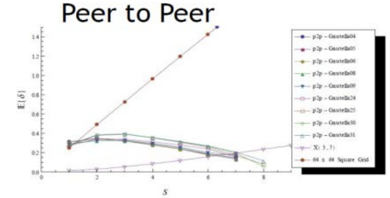
Application

Social Network



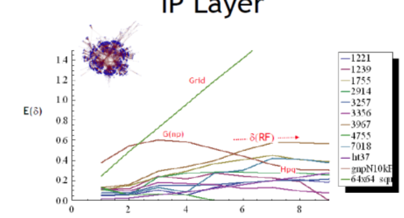
Protocol

Peer to Peer



Architecture

IP Layer



Entropy Classes for Dynamic Network Models

Lizhong Zheng, MIT

Approach: Deriving models for network protocol analysis has assumed fixed protocols without the benefit of feedback or dynamic correlations in coding and protocol. Using Renyi correlation analysis and entropy to model this wider class of models allows greater flexibility in describing statistical classes.

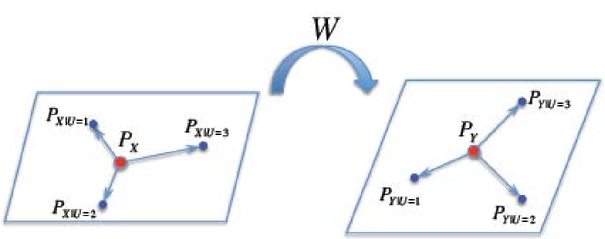
Payoff: Complex phenomena such as feedback in coding can be modeled under dynamic heterogeneous conditions.

Network Channel Architecture

Feedback Channel & Geometric Invariants

$$X \longrightarrow \boxed{W} \xrightarrow{\;Y\;}$$

$$P_{X|U=u} = P_X + \epsilon \cdot [\sqrt{P_X}] \cdot L_u$$



Renyi Channel Correlation Analysis

(connected to geometric curvature)

- Maximal correlation, a measure of dependence:

$$\rho(X,Y) \triangleq \sup_{f(X),g(Y):E[f]=E[g]=0,E[f^2]=E[g^2]=1} E[f(X)g(Y)]$$

- Conditional Expectation Operator: $B : \mathcal{F}_Y \mapsto \mathcal{F}_X$

$$B(f) = E[f(X)|Y]$$

- Renyi

$$\rho(X,Y) = \sup_f \frac{E[(B^\dagger B(f))^2]}{E[f^2]}$$

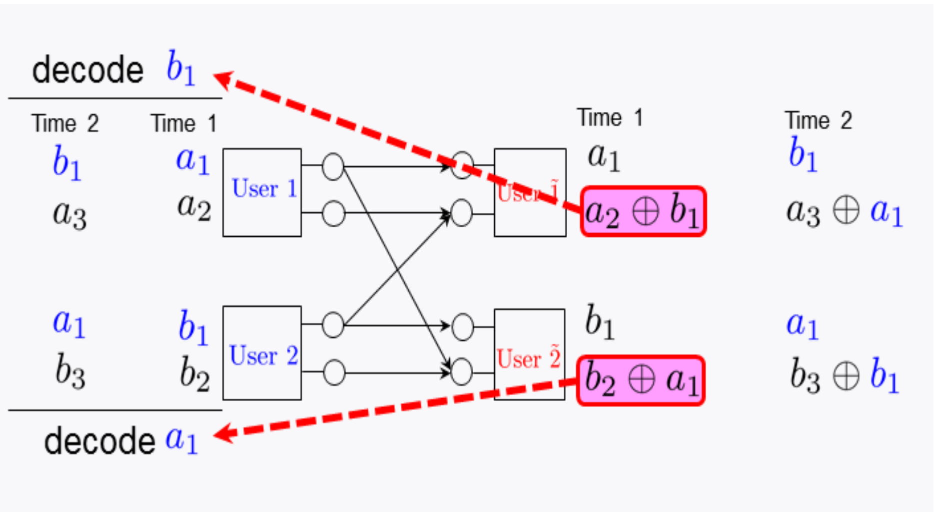
Feedback in Coding Theory

D. Tse, Berkeley, P. Gupta, Alcatel Lucent, D. Shah, MIT

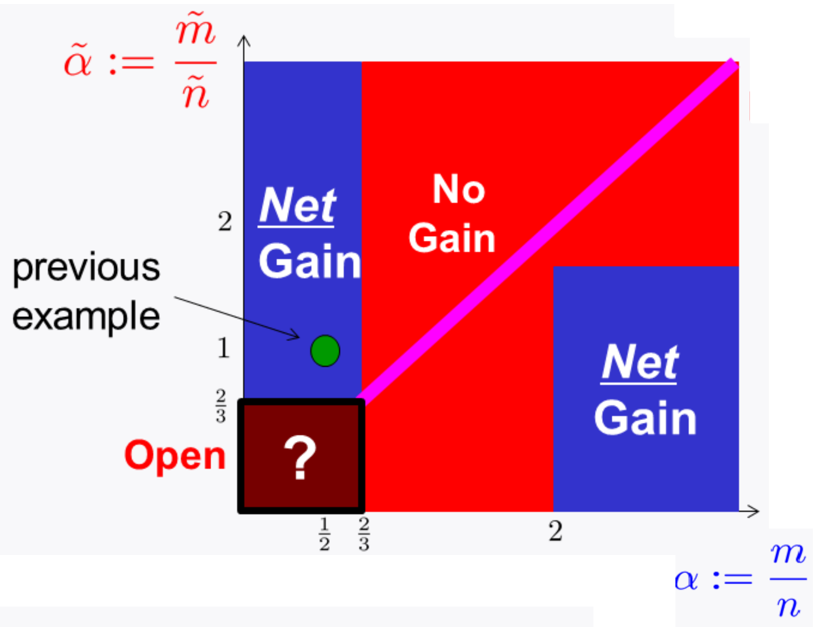
Approach: Coding theory classically assumes fixed statistic and fixed methods of coding for a given set of network and interference conditions

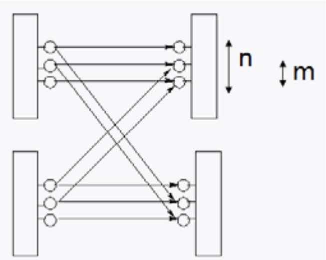
Payoff: Feedback in coding methods can significantly improve throughput under dynamic network and interference conditions

Feedback Coding Approach



Areas Where Improves Performance (including side information)



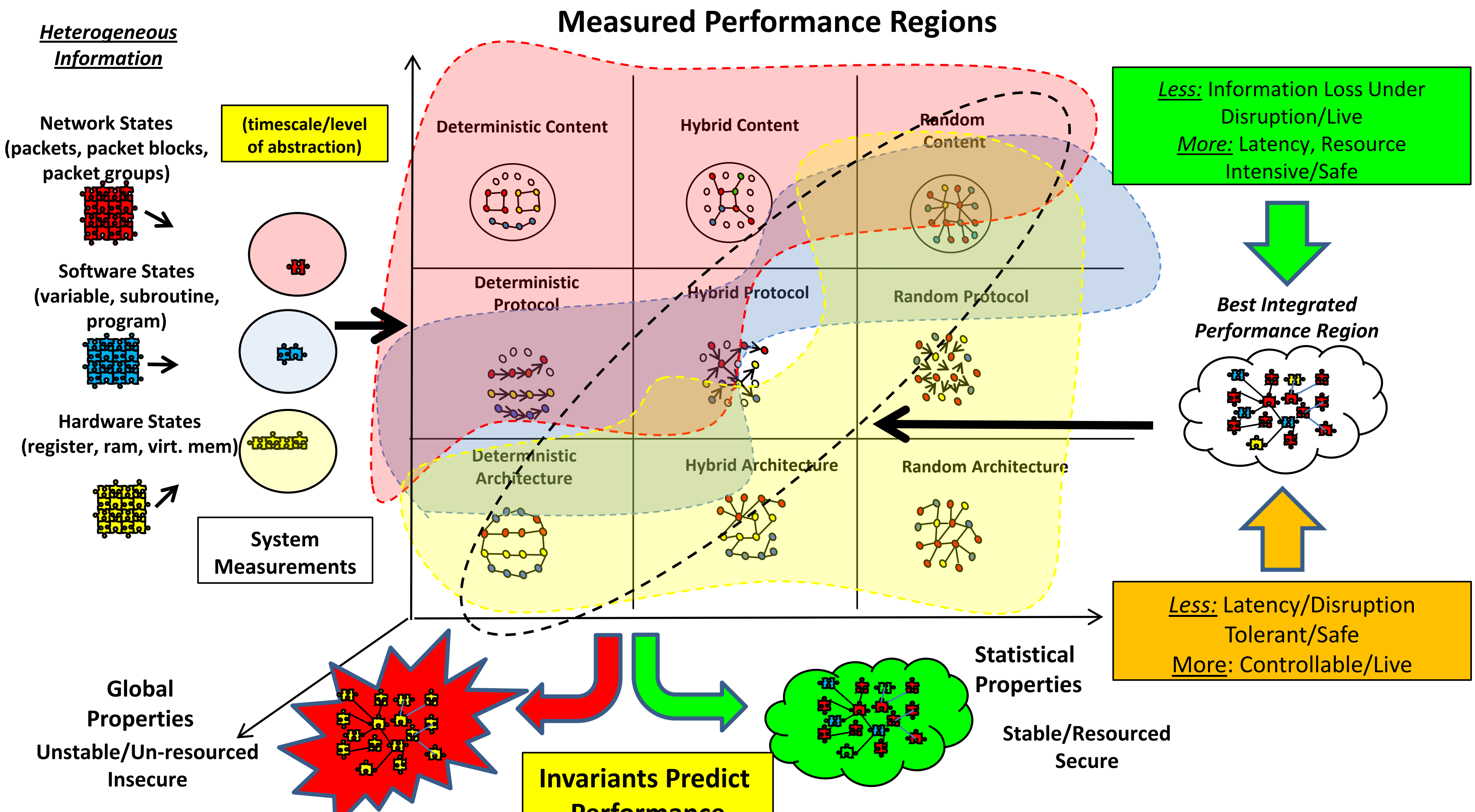


$$\frac{m}{n} = \frac{\log \mathrm{INR}}{\log \mathrm{SNR}}$$

INR = interference-to-noise ratio

Information Systems Assessment

Predict system performance using mathematical invariants from measured data



Hodge Theory for Invariants in Network Algorithms

ST Yau, Harvard, Ali Jadbabaie, UPenn, Fan Chung Graham, UCSD

Approach: Hodge decompositions allow natural functional invariants to be used on extremely complex structures

Payoff: Analysis of Hodge decomposition can be applied to whole classes of networks to characterize invariant parameters and predict performance.

Hodge Decomposition Gives Powerful Functional Invariants

The k-Laplacian acting on $C^k(X)$ is defined by

$$\Delta_k = \partial_{k+1}\partial_{k+1}^* + \partial_k^*\partial_k$$

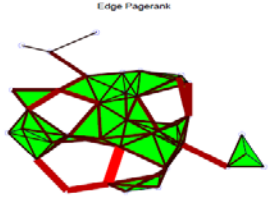
- $\Delta_k f = 0 \iff \partial_k f = 0$ and $\partial_{k+1}^* f = 0$
- $C^k(X) = \ker \Delta_k \oplus \mathrm{Im}(\partial_{k+1}) \oplus \mathrm{Im}(\partial_k^*)$ is an orthogonal decomposition called the Hodge decomposition.

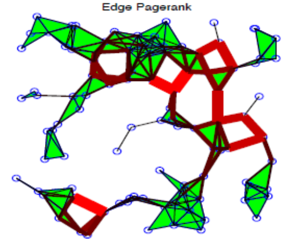
- Write $\chi_e = h_e + g_e + c_e$
  - $g_e = \mathrm{proj}_{\mathrm{Im}\partial_1^*}(\chi_e)$: Gradient flow
  - $c_e = \mathrm{proj}_{\mathrm{Im}\partial_2}(\chi_e)$: Curl flow
  - $h_e = \mathrm{proj}_{\ker \partial_2^* / \mathrm{Im}\partial_1^*}(\chi_e)$: Harmonic flow

Invariant Analysis of Page Rank (Google)

PageRank $\quad pr(\alpha, s) = \beta s D^{-1/2} \mathcal{G}_\beta D^{1/2}, \quad \beta = 2\alpha / 1-\alpha$

Invariant Analysis of Google's Page Rank Algorithm for Different Values of Beta





Topological Invariants for Model Checking
Network & System Dynamics

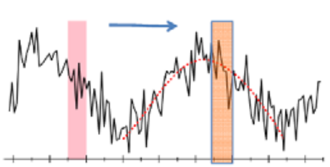
John Harer/Sayan Mukherjee Duke Konstantin Mischaikow/Rutgers, Samson Abramsky Oxford, Peter Chin Johns Hopkins

Approach: Dynamic measured data has correlated structures that are difficult to characterize by standard tools in algebraic topology such as homology. Additional features such as Conley index can augment invariants provided by algebraic topology.

Payoff: Dynamic modes of networks and networked systems can be captured by new methods in discrete Morse theory and algebraic topology to predict performance

Dynamic Time Series

Initial Time Series



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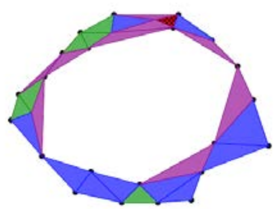
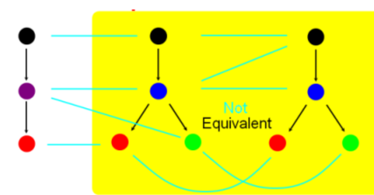
Geometric Invariant (homology)



Use of Conley Index Allows Verification of Dynamics for System Assurance

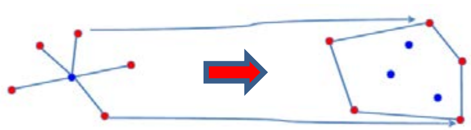
Model Equivalence Checking



Time Series Data

Graphs from Time Series

Graphs With Invariant Cycle



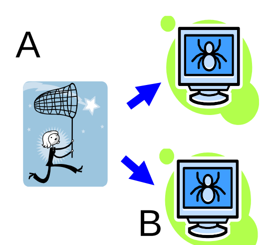
Conley Index

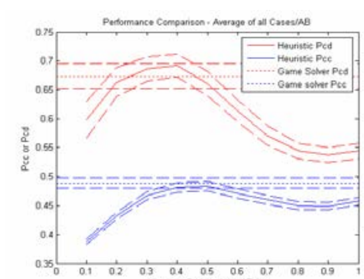
$f: \mathbb{R}^n \to \mathbb{R}^n$

Given $\mathcal{F}: \mathcal{X} \rightrightarrows \mathcal{X}$ and $\mathcal{P}_0 \subset \mathcal{P}_1 \subset \mathcal{X}$ need to compute

$f_*: H_*(|\mathcal{P}_1|/|\mathcal{P}_0|, [|\mathcal{P}_0|]) \to H_*(|\mathcal{P}_1|/|\mathcal{P}_0|, [|\mathcal{P}_0|])$

Bugs and System Instabilities Can Be Measured and Model Checked in Real Time





Categorical Invariants on Information Flows

Rob Ghrist, UPenn

Approach: Dynamic network information flow can be parameterized by its max flow min cut value relative to the network topology

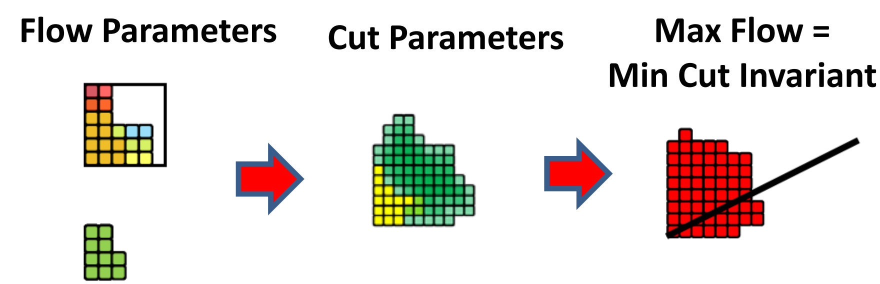
Payoff: Categories of flows can be developed using sheaf theoretic formulation for max-flow min-cut parameters to characterize and verify system performance

Sheaf Formulation For Max Flow Min Cut and Network Code

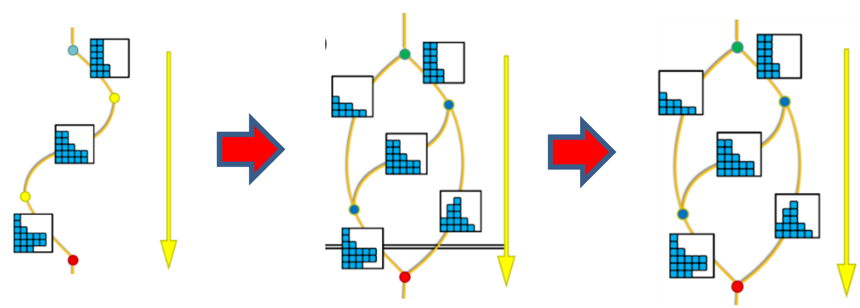
$$\begin{tikzcd}
(O\otimes F)_X \arrow[r] \arrow[dr] & (O\otimes F)_{cut} \arrow[d] \\
 & (O\otimes F)_{pt}
\end{tikzcd}$$

$$\begin{aligned}
[0,\text{maxflow}] &= \textstyle\bigcup_{\text{flows}}[0,\text{flowval}] \\
&= \text{im}\ (O\otimes F)_X \to (O\otimes F)_{pt} \\
&= \text{im}\ \lim_{\text{cuts}}(O\otimes F)_{cut} \to (O\otimes F)_{pt} \\
&= \lim_{\text{cuts}}\ \text{im}(O\otimes F)_{cut} \to (O\otimes F)_{pt} \\
&= \lim_{\text{cuts}}[0,\text{cutval}] \\
[0,\text{mincut}] &= \textstyle\bigcap_{\text{cuts}}[0,\text{cutval}]
\end{aligned}$$

Categorical Invariants For Coded Information Flows



Corresponding Network Flow Conditions

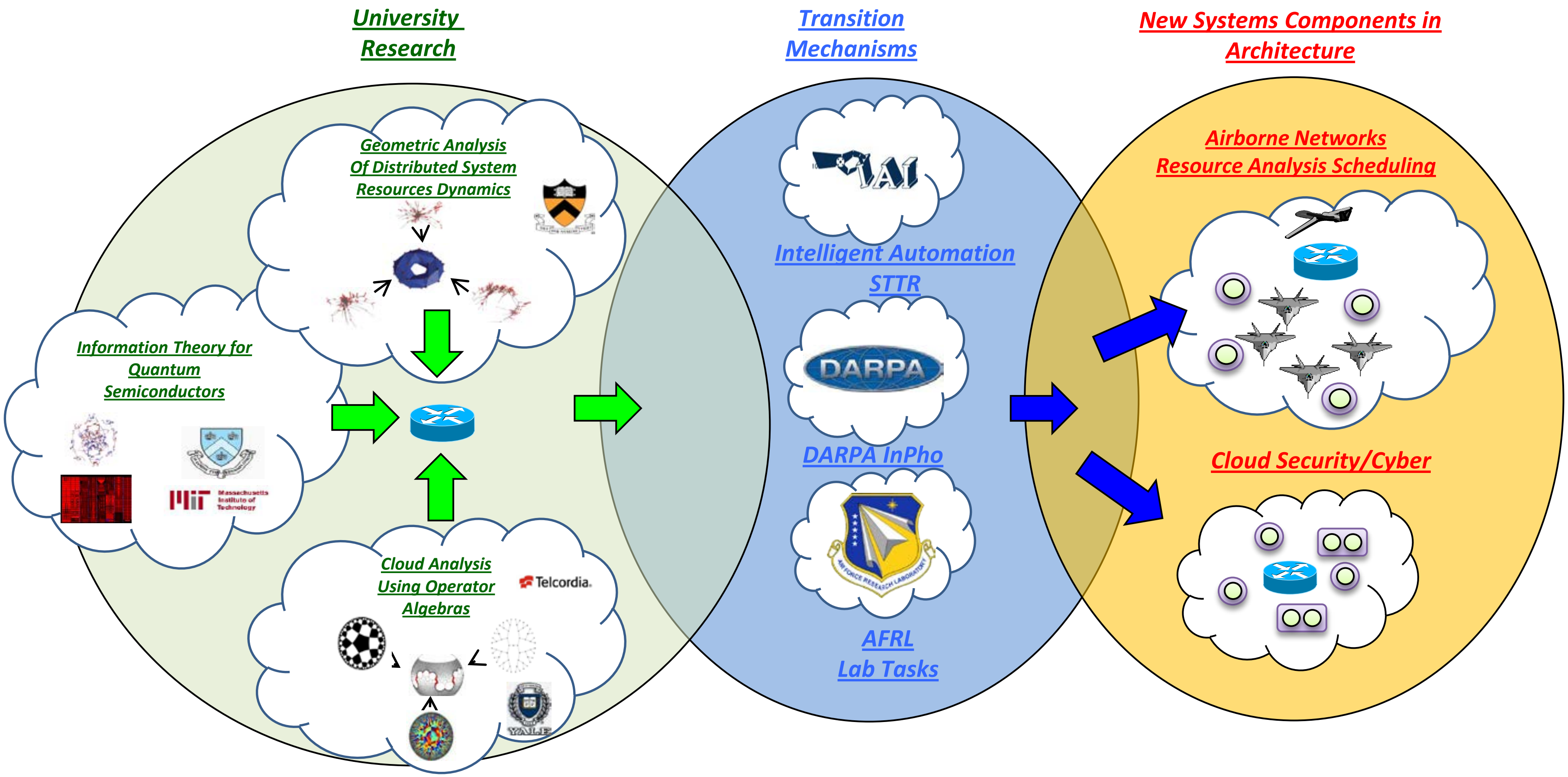


Joint project with DARPA/DSO GRAPHS program

Complex Networks Transition Activities

Complex Networks uses advanced mathematical analysis of information systems measurements to resource, verify, and secure distributed Air Force infrastructures

- Princeton MURI – dynamic analysis of packets for airborne network resource management
- Yale/Telcordia commercial grant – real time system security policy verification
- Columbia/MIT – information theory for new quantum semiconductors



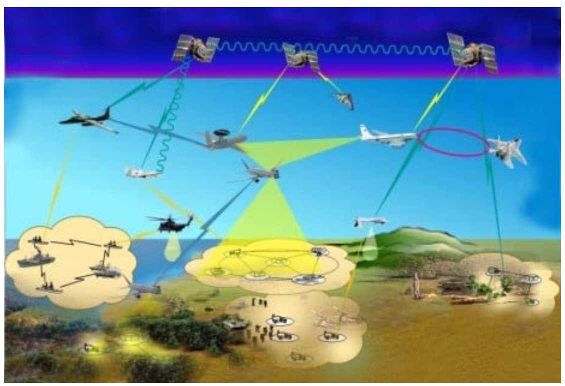
Space and Airborne Cognitive RF

Scott Erwin, AFRL/RV, John Matyjas, AFRL/RI, Vasu Chakravarthy, AFRL/RY

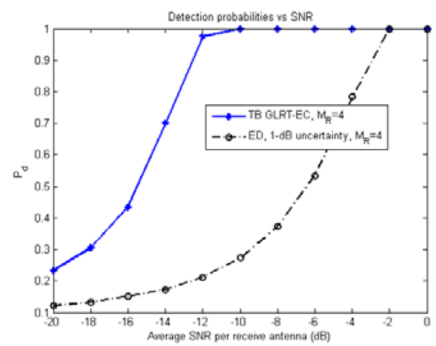
Approach: Use advanced non-parametric geometric measurement and game theoretic techniques with Generalized Likelihood ratio test to enable training on RF interference data in conjunction with advanced MIMO beam-forming techniques to remove interference

Payoff: AF will be able to conduct operations in crowded dynamic spectrum environment

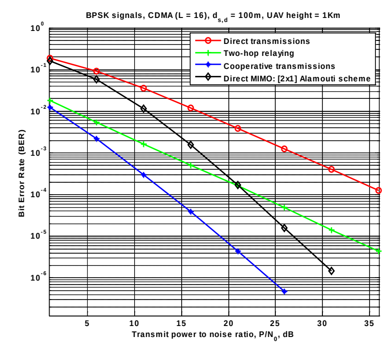
Complex RF Environment



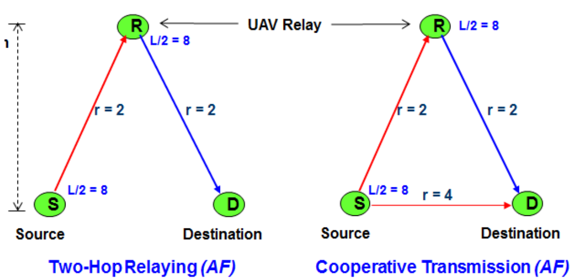
Improved Detection



Improved Throughput



Space Time Network



Network Measurement & Invariants

Adaptive Detection

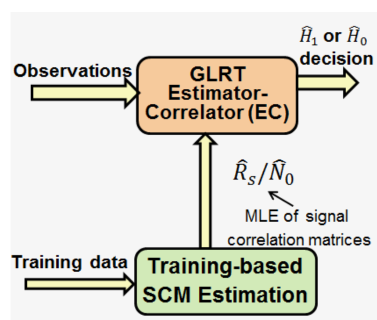


Fig: The structure of the GLRT-EC detector.

$$\Lambda_{GLRT} = \sum_{n=0}^{N_s-1} ln \frac{P(x|H_1, \hat{R}_s)}{P(x|H_0, \hat{N}_0)} =$$

$$\sum_{n=0}^{N_s-1} x^H[n]\hat{R}_s(\hat{R}_s+\hat{N}_0 I)^{-1}x[n]/\hat{N}_0$$

Quantum Network & System Measurements

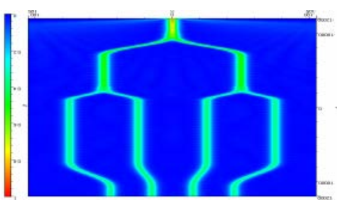
Jeff Yepez/AFRL/RD, Paul Alsing/AFRL/RI, Atilla Szep, AFRL/RY

Approach: Verification of classical vs. quantum states in a network provides a new class of measurement problems which need invariants for analysis of states of large scale quantum systems for information assurance, communication, and computing

Payoff: Integrating new invariant network techniques with new quantum representations will allow a much more integrated way of analyzing large scale quantum network and computational systems

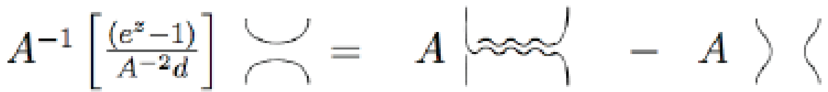
Data from Quantum Network & System Measurements

Photonic Device Measurements

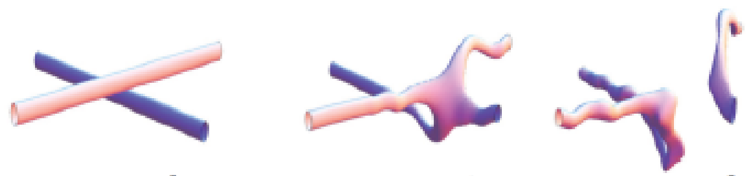


Optical Measurements

Representation of Quantum Logic



crossed quantum gate uncrossed



crossed $t=0$ reconnection $t=48$ uncrossed $t=116$

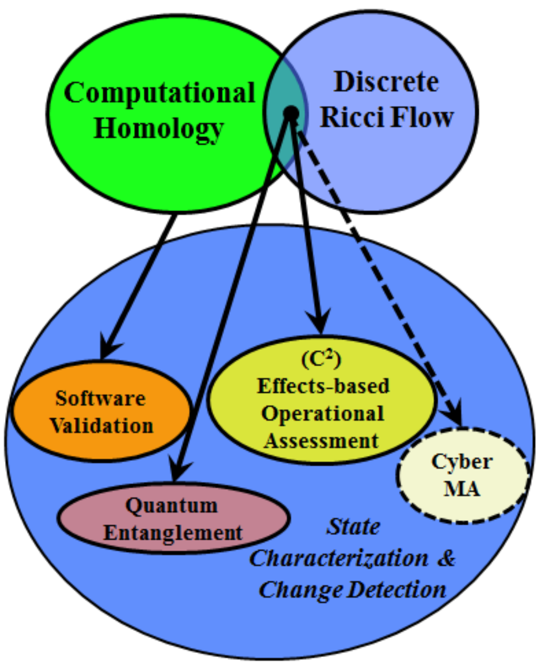
New MURI 2012: Measurement and Verification in Quantum Information Systems

Computational Homology and Ricci Flow for Verification of Classical and Quantum States

Paul Alsing/AFRL RI, Howard Bramson/Syracuse, Warner Miller, FAU

Approach: Verification of classical and quantum states in a network and system provides a new class of measurement problems which need invariants such as computational homology for analysis of states

Payoff: Integrating new invariant network techniques with new classical and quantum representations will allow a much more integrated way of analyzing & securing large scale networked and computational systems



Network Information Properties Of Curvature

Classical Information

Triangle Inequality

$$\mathcal{D}_{AB} + \mathcal{D}_{BC} \geq \mathcal{D}_{AC}$$

Polygonal Inequality

$$\mathcal{D}_{AB} + \mathcal{D}_{BC} + \ldots + \mathcal{D}_{YZ} \geq \mathcal{D}_{AZ}$$

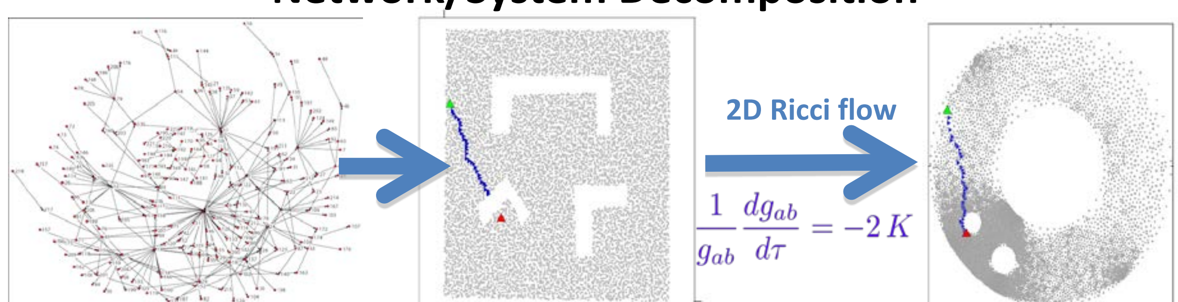
Quantum Information

Triangle,…,Polygonal Inequalities *are* violated

$$|\psi\rangle = \left(|\uparrow_1,\downarrow_2\rangle - |\downarrow_1,\uparrow_2\rangle\right)/\sqrt{2}$$

$$\Rightarrow \exists \text{ no } P(A_1, B_2, C_1)$$

Network/System Decomposition



Complex Networks Invariants for Risk Assessment Measurement of Human vs. Machine Performance

Leslie Blaha, AFRL/RH

Approach: Complex Networks invariants can be used to assess risk on human vs. machine operation when faced with complex decision task.

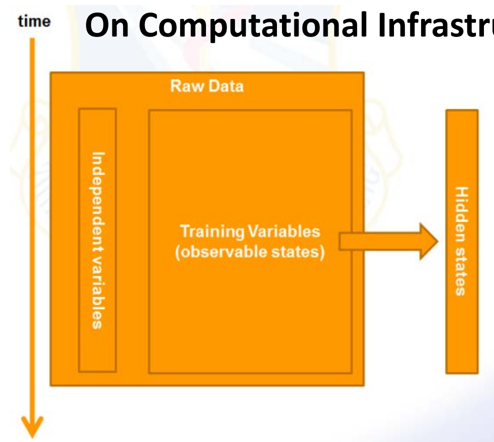
Payoff: Detailed understanding and automation of how to trade human vs. machine performance in time critical functions such as cyber security, autonomous operation of air vehicles

Warfighter

Measurement

Performance and Representation

Machine Learning
On Computational Infrastructure



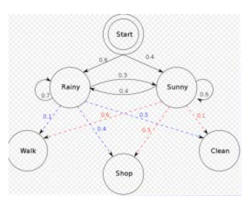
Estimate Decision Risk
Using Complex Network Invariants

Human Risk Lower

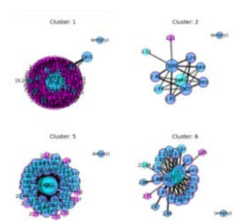
Human Behavior

t	Observed sequence	Hidden sequence
1	Walk	Sunny
2	Walk	Sunny
3	Shop	Rainy
4	Clean	Rainy
5	Shop	Rainy
6	Walk	Sunny
7	Clean	Sunny

Hidden Variable Theory



Network Representation



Machine Learning Risk Lower

Recent Program Awards

- **Dan Speilman**
  - MacArthur Genius Award (2012)
- **Ingrid Daubechies**
  - Fellow of the American Mathematical Society 2012
  - Benjamin Franklin Institute Medal, 2012
  - Leroy Steel Prize From American Mathematical Society 2012
  - IEEE Jack Kirby Signal Processing Medal 2011
- **Robert Calderbank**

  - IEEE/Hamming Medal Winner (2012)
- **Vincent Poor**

  - National Academy of Science (2011)
- **Emmanuel Candes:**
  - Collatz Prize (Mathematics) , (ICIAM) (2011)
  - Winner, Sixth Vasil A. Popov Prize (Mathematics) ,(2010)
- **ST Yau**
  - Wolf Prize Mathematics, 2010
- **Joel Tropp:**
  - Eighth Monroe H. Martin Prize, 2011
- **Yonina Eldar**
  - IEEE Fellow 2013
- **Mung Chiang**:
  - IEEE Fellow 2012
  - IEEE Kiyo Tomiyasu Award in 2012
- **Junshan Zhang**
  - IEEE Fellow 2012

Academia/Commercial Outreach

- Keynote Lecture, American Society of Mechanical Engineers, Complex Systems 2012
- Keynote Lecture, International Conference on Complex Networks, 2012
- Keynote Lecture, IEEE, CogSima, 2013
- Invited Lecture, Yale Mathematics, Anniversary of Coifman, Jones, Rokhlin Achievements
- Organizer: London Institute of Mathematics: Mathematics of on Statistical Verification, March 2012
- Organizer, OSTP Meeting on Complex Engineered Systems, 2012
- Invited Speaker, Allerton, IEEE Conference on Information Theory, University of Illinois 2012
- Invited Speaker, IDGA Big Data, Federal Meeting Washington DC, 2013
- Invited Speaker, Neuro-Information Processing, Lake Tahoe, 2012
- Invited Speaker: Dagstuhl Germany, Mathematics of Information Flow, 2012
- Invited Speaker: USCD Information Theory and Applications, LaJolla 2013

Program Impact & Collaboration with Agencies

- OSTP/NITRD – Co-Chair Large Scale Networks Working Group

  - New national thrust – Complex Networks and Systems inspired by AFOSR program – Workshop "Complex Engineered Networks" organized by leader of AFOSR Complex Networks MURI "Information Dynamics in Networks"
- ASDR&E

  - Engineered Resilient Systems – Complex Networks and Foundations of Information Systems on Roadmap
- DARPA Collaboration/joint program reviews
  - Graphs – Mathematics of graphs and networks agent
  - Defense Science Office Mathematics Advisory Panel
  - InPho – Information in a photon/quantum network collaborative funding
  - Com-EX cognitive network program transition agent
- IARPA – Quantum Computer Science Working Group
- ARL/ARO Network Science Board of Advisors
- NSF Future Internet, Cyber Physical Systems

Complex Networks Trends

- **Local Network Theory**
  - Geometric and binary information coding
  - Coding information with network performance objectives
  - Integration with verification and quantum methods
- **Network Management**
  - Nonparametric strategies for assessing network performance
  - Distributed strategies for measuring and assessing network information transfer
  - Sparse network management
- **Global Network Theory**
  - Geometric flow analysis for prediction and management of network performance
  - Global state space taxonomy and categorization
- **Information Systems Research**
  - Combined network, software, and hardware analysis
  - Defining correct input data for given mathematical assessment
  - Invariant metrics for analysis of network performance

Other Program Interactions

Cyber Operations: **Joint University Center of Excellence:**
"Cyber Vision 2025" – Enabling Technologies workshops
"Secure Cloud Computing" with university and AFRL/RI

Dynamics and Control : **Verification and Validation of Complex Systems**

Physics and Materials: **New Joint MURI Topic: "Large Scale Integrated Hybrid Nanophotonics"**

Socio-Cultural Analysis: **Social Networks – Joint MURI Topic: "Stable Metrics for Inference in Social Networks " – UCLA/USC/ASU**

Quantum: **Interaction with quantum network and quantum estimation processes through lab tasks**
- Joint EOARD initiative at Cambridge

Information Fusion: **Critical feature selection in sensor networks**
Optimization: **Competing optimization requirements.**
Decision: **Networks of neurons.**
Biology: **Systems biological processes as networks.**

Transition Activities

- **AFRL**
  - AFRL/RI – Cyber Vision 2025 workshops/Illinois Center for Secure Cloud Computing/
  - AFRL/RI/RY – DARPA InPho program/DARPA Graphs program
  - AFRL/RI/RY/RV – distributed secure space communications
  - AFRL/RW/RV/RH – verification and validation of complex systems

- **STTR**
  - Intelligent Automation: Transition to ESC of Airborne Networks management – transition to Boeing for test-bed
  - Avirtek: Secure router application interface- AFRL/RI
  - Andro – Joint Spectrum Center Lockheed transition of automated spectrum management tool

Transition Activities

- Customer/Industry
  - Collaboration with ACC/GCIC, Air Force Spectrum Management Agency on JALIN ICD
  - Collaboration with Boeing, ESC, IAI for transition of coding and routing management protocols baseline CORE tools to Rome Lab for possible integration in CABLE JCTD
  - Briefing to Space Command/Peterson for potential collaboration
  - Interaction with Northrop Grumman/BACN airborne networking program for potential collaboration
- OSD
  - Complex Systems Engineering and Systems 20/20 initiative
  - Software Assurance and Security Initiative
  - Robust Command and Control Initiative
- Commercial
  - Interaction with Stanford on real time network information recovery
  - New initiatives with Akamai for content distribution analysis
  - Interaction with USFA/DHS/CISCO on router algorithm design